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BEAM INJECTION ASSESSMENT

OF DEFECTS IN SEMICONDUCTORS

INTERNATIONAL WORKSHOP

18-19-20 JULY 1988

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MEUDON-BELLEVUE (FRANCE)

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Beam Injection Assessment of Defects in Semiconductors

International Workshop

18 - 19 - 20 JULY 1988

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MONDAY 18 JULY 88

Chairmen :			
		8h30	Registration
		9h	Welcome
H.U.HABERMEIER	Session 1	9h30	SEM microcharacterization of semiconductors by EBIC and CL. D.B. HOLT
		10h30	Electron and photon-matter interaction. E. NAPCHAN
		11h30	Break
A.JAKUBOWICS	Session 2	12h	Modelling of the EBIC measurements of diffusion lengths and the recombination contrast. C. DONOLATO.
		14h	POSTERS
G.R.BOOKER	Session 3	16h	Minority carrier diffusion length : measurement by EBIC, connection to material microstructure. M. KITTLER, W. SEIFERT.
		17h	ROUND TABLES : parallel sessions 1) A. JAKUBOWICZ 2) J.-F. BRESSE
		19h	SOCIAL EVENT : wines and songs.

TUESDAY 19 JULY 88

M. WILSHAW	Session 4	9h	STEM-catholuminescence... J.W. STEEDS
		10h	Intrinsic or extrinsic origin of the recombinations at defects. B. SIEBER
		11h	Break
A.ROCHER	Session 5	11h30	LBIC quantitative mapping. A. LAUGIER
		14h	POSTERS
W.SCHRÖTER	Session 6	16h	Scanning DLTS. O. BREITENSTEIN
		17h	ROUND TABLES : paralell sessions. 1) J.-L. MAURICE 2) W. SCHRÖTER

WEDNESDAY 20 JULY 88

M.DUPUY	Session 7	9h	CL in laser heterojunctions. P. HENOC
		10h	CL in quantum-wells. J. CHRISTEN
		11h	Break
Y.MARFAING	Session 8	11h30	Electron and optical beam testing of integrated circuits. J.P. COLLIN
		14h	ROUND TABLE D.B. HOLT
		15h	POSTERS AND FAREWELL TEA.
		16h30	END of the workshop.

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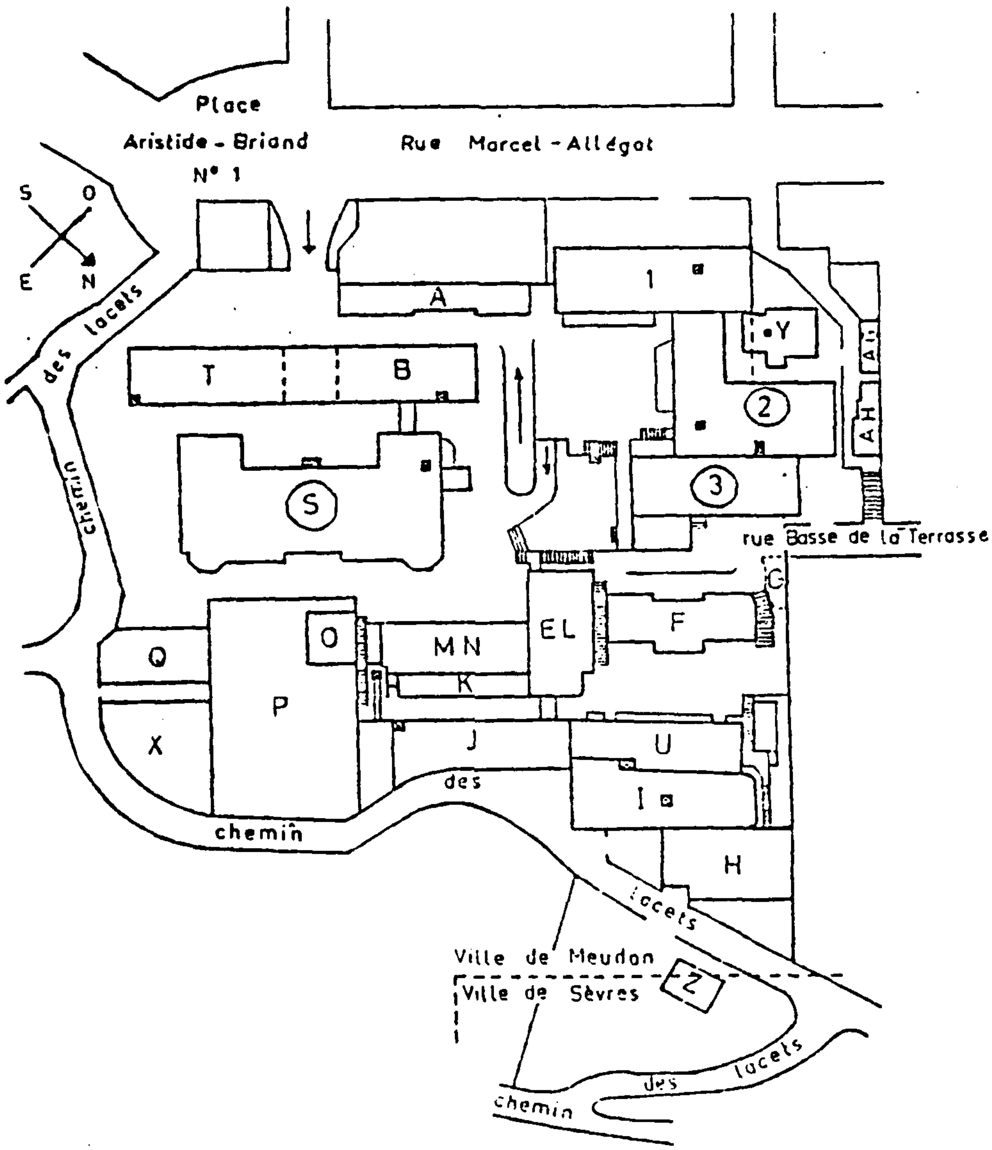

S = salle des conférences

3 = salle "des directeurs" - Sessions Poster

2 = Restaurant - cafeteria

LECTURE ABSTRACTS

Scanning-DLTS

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Scanning Deep Level Transient Spectroscopy (SDLTS) is a current SEM technique for the detection of the local distribution of deep level centres in semiconductors /1, 2/. It is based on the application of the widely used DLTS technique measuring capacitance - or current transients on a space charge structure after excitation pulses as a function of the temperature. By means of Scanning-DLTS - i.e. the excitation of the levels by an electron probe - deep level states can be investigated spectroscopically with a spatial resolution of a few microns. Scanning the pulsed electron beam (at a temperature selected according to an interesting energy level) yields an SDLTS image, and scanning the sample temperature with the electron beam fixed at a certain position yields the DLTS spectrum being specifically for this very position (Local DLTS).

The contribution deals with the physical foundations of the SDLTS technique and it discusses the demands on the instrumentation. The measurement practice is described and illustrated on several experimental examples. Finally, the possibilities and limitations of SDLTS are critically reviewed.

References

/1/ P.M. Petroff, D.V. Lang, Appl. Phys. Lett. 31, 60-62, 1977
/2/ O. Breitenstein, J. Heydenreich, Scanning 7, 273-289, 1985

LATERAL MAPPING OF ATOMIC SCALE INTERFACE MORPHOLOGY AND DISLOCATIONS IN QUANTUM WELLS BY CATHODOLUMINESCENCE IMAGING

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Our present knowledge of the atomic scale structural, chemical and electronic properties of semiconductor interfaces is inversely proportional to their importance for a whole generation of novel electronic and photonic quantum well devices. It is the purpose of this paper to demonstrate how wavelength- and time- resolved cathodoluminescence imaging (CLI) provides a one-to-one image of the crystallographic island structure of the heterointerfaces which are the boundaries of the quantum well.

A detailed description of the fully computer controlled cathodoluminescence (CL) system is given. The accelerating voltage, which is choosen to be 30 kV in our standard CL work, is lowered to 3 kV in order to reduce the diameter of the carrier generation volume resulting in an increase of the lateral CL resolution. The exciting electron beam is digitally scanned over a sample area divided in up to 512 x 400 pixels. The CL signal is detected in the visible and near infrared regime (GaAs quantum wells) by a cooled photomultiplier using the technique of time resolved single photon counting. The total time resolution is better than 250 ps. Our data acquisition technique has the unique advantage that simultaneously up to 14 time windows can be activated, enabling us to record up to 14 spectra or up to 14 images corresponding to different times with respect to the start of the exciting pulse in a single run.

Results on AlGaAs/GaAs/AlGaAs quantum wells are presented as a typical example. Direct images of growth islands differing by one monolayer height (2.8 Å) at GaAs/AlGaAs heterointerfaces and of the columnar structure of GaAs QW's are observed. The dependance of the lateral extension of these islands, which for certain growth conditions exceeds 6-7 µm, on the parameters of crystal growth is investigated. A transition from 2 dimensional to 3 dimensional crystal growth due to an increase of the MBE growth temperature from 600 °C to 620 °C is clearly observed.

Spectrally- and time-resolved CLI experiments directly visualize the lateral diffusion of the quasi two dimensional carriers along the quantum well interfaces and provide a measure of the in-plane diffusion velocity in quantum well structures.

The CLI detection setup is further extended to the infrared regime, by adapting avalanche photodiodes to the photon counting system. This enables CLI and time resolved CLI investigation of InGaAs quantum wells and related material systems.

Strain induced dislocations in pseudomorphic strained layer quantum wells (e.g. GaAs/InGaAs/GaAs QW's) are directly visualized by infrared CLI. Time resolved experiments yield lifetime images arround these dislocations.

ELECTRON AND OPTICAL BEAM TESTING OF INTEGRATED CIRCUITS

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The evolution of Integrated Circuits technology and architecture is pushing today the associated test and characterization technology to even higher levels.
The test must not only present even higher parametric performances like voltage, temporal ans spatial resolutions and a good fault coverage but also high level functionalities like a CAD link and automation capabilities.
Each and all of these characteristics, when they are identified as measurement and functional performances, need more and more of an alternative to the standard approach of the external electrical test and the internal mechanical probing.
This alternative does exist and corresponds to a set of techniques which are generally qualified as internal contactless testing techniques. Although some of them have been introduced and used for many years, the recent last years have seen their diffusion into the industry through commercial equipments : it is the case of E. Beam testing and photoexcitation which are fast becoming standards of the Integrated Circuits bulk production characterization and test. For the most advanced Integrated Circuits and package technology, some other new techniques have been more recently introduced to address the typical needs of the "beyond one micron and/or the 50 picoseconds gate delay". This is for example the case of HJBTs or HEMTs devices.
This paper presents an overview of E. Beam testing and laser testing techniques detailing their principle and giving for them application examples in the domain of Integrated Circuit failure analysis and characterization. Finally, as it is clear that no single test technique can provide a cost and technical effective answer to the wide range of applications and needs and that a divide-and-conquer approach seems more appropriate, a comparative study will be presented.

MODELING THE EBIC MEASUREMENTS OF DIFFUSION LENGTHS AND THE RECOMBINATION CONTRAST AT EXTENDED DEFECTS

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Summary

Modeling of EBIC experiments is usually done by describing: a) the generation of electron-hole pairs in a semiconductor by the electron beam; b) the diffusion of beam-injected minority carriers and their recombination in the bulk, at the surface and extended defects; c) carrier collection by a Schottky or p-n junction.

The alternative description proposed here relies on the notion of charge-collection probability $\varphi(\underline{r})$, i.e. the probability that a minority carrier generated at $\underline{r}$ will be collected by the junction. It is shown that the distribution $\varphi(\underline{r})$ in a given device can be found by solving a homogeneous diffusion equation, and the induced current is the result of probing this device property with the generation function of the electron beam.

The most frequent EBIC experiments are revisited using this approach and in some cases a simplification of the mathematical treatment is obtained. It is shown that some useful methods of recovering semiconductor or defect properties from EBIC measurements make use of asymptotic or average (integral) properties of φ. In particular, the use of the EBIC contrast profile area (instead of the maximum contrast) for establishing the recombination strength of defects allows a reduction of the number of dimensions of the corresponding contrast model.

CATHODOLUMINESCENCE IN DOUBLE HETEROJUNCTION LASERS

P. HENOC, B. AKAMATSU, R.B. MARTINS

The cathodoluminescence mode (CL) of the Scanning Electron Microscope (SEM) allows evaluating local properties of the active layers of double-heterojunction lasers. In the CL mode the phenomenon of carriers separation caused by a space charge region is generally avoided by the observation of heterostructures without electrical junction; but this observation is not usable for a laser characterization because some problems at the heterotype junctions can also occur.

The application of an external bias or the creation of an internal polarization due to a local accumulation of carriers under electron bombardment, may also be used to avoid this phenomenon. The analysis of the CL signal from cleaved laser facets as a function of the external bias and of the incident beam power gives three regimes. The first one is a regime of non-radiative recombination, dominated by traps located in the active layer itself or at interfaces. The second one corresponds to spontaneous emission: it begins when traps are saturated and varies linearly or quadratically with the injected current, depending on whether the injection is low or high. The third one is superlinear and corresponds to stimulated emission. Analysing the extension of theese regimes, it is possible to obtain a local evaluation of the interface quality, of the internal efficiency of the active layer and of the local gain.

To explain quantitatively the results we propose an analytical form of the tridimensional generation function, derived from a Monte Carlo trajectory simulation. The spatially averaged quality and spatial homogeneity of GaInAsP double-heterojunction lasers have been observed with spectroscopically resolved CL.

SEM MICROCHARACTERIZATION OF SEMICONDUCTORS BY EBIC AND CL

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Abstract - Scanning electron microscope (SEM) EBIC (electron beam induced current) and CL (cathodoluminescence) methods are set in perspective by a brief survey of techniques of value in the inspection and characterization of semiconducting materials and devices. EBIC and CL observations can be made in conventional SEMs. in dedicated. ultra-high vacuum STEMs (scanning transmission E.M.s) and in Temscan-type instruments (transmission E.M.s with scanning facilities) and the relative merits of these instruments are outlined.

Several recent advances in SEM EBIC and CL microcharacterization (physical property measurements with a spatial resolution of a μm) are emphasised to provide a perspective for a brief account of some current developments in these fields.

The availability of theoretical treatments make it possible to extract reliable values of electronic and luminescence properties.
The emergence of quantitative EBIC and CL defect contrast theories makes possible the determination of the recombination strengths and other characteristics of defects giving dark contrast. Microcomputer Monte Carlo programs are now available for the simulation of electron trajectories and the computation of energy dissipation distribution and hole-electron pair generation functions. These can be used to compute EBIC and CL contrast profiles. which makes the extraction of physical parameter values from the data far more practical.

EBIC analyses are being extended to a number of challenging new problems One of these is bright or dark/bright defect contrast. Another is the microcharacterization of Schottky barriers with non-uniform heights and charge collecting barriers such as heterojunctions. whose energy band diagram is unknown. The application of image processing to VSLI circuits for the rapid location of defects is progressing. Warwick has given an interesting first discussion of the MAS corrections. analogous to the well-known ZAF corrections for EPMA (electron probe microanalysis), that will be needed for quantitative CL microanalysis.

MINORITY-CARRIER DIFFUSION LENGTH: MEASUREMENT BY EBIC, CONNECTION TO MATERIALS MICROSTRUCTURE AND RELATION TO DEVICE PERFORMANCE

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Institute of Semiconductor Physics, Frankfurt(Oder), DDR-1200

After an introduction to recombination phenomena, with particular emphasis on silicon, the existing different EBIC techniques for diffusion-length measurement in homogeneous material are discussed and compared. A new technique developed recently by us is described.
Diffusion-length measurement in thin layers is briefly treated, too. Further, a method for evaluation of diffusion-length depth profiles is given and its utilization for characterization of intrinsically gettered silicon is demonstrated.
The contribution of closely neighboured defects having EBIC contrast to the mean diffusion length is investigated. The application of the derived formulae to heat-treated Cz silicon is discussed and allows to identify essential sources of bulk recombination in this kind of material.
It is demonstrated that more detailed information about recombination processes may be obtained from diffusion-length measurements (e.g. energetic levels of recombination centres, concentration of interstitial iron in boron-doped Si).
Diffusion-length-related effects on device behaviour are dealt with, too, showing that diffusion-length measurements may be useful in the context of a 'lifetime engineering'.

LBIC QUANTITATIVE MAPPING

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A localized source of excess carrier in semiconductors can be produced by a finely focused ionizing beam. With a suitable structure of collection - namely a p/n or Schottky junction - the generated carriers give a current available in an external circuit. Analysis of the signal thus obtained can provide valuable information on the local transport properties of the material under test.

Primarily, the surface probing can be carried out either by an electron-beam or by a light-beam. The method of electron-beam-induced-current (EBIC) characterization has been widely used and several attempts have been made to characterize the signal thus emitted. However, many of the experiments possible with the EBIC mode can be performed using a light-beam as the excitation source.

The aim of this paper is to give a review of the physical parameters that may be obtained using the LBIC method. To quantitatively interpret the induced current signal, several conditions are required, in particular: (i) a measurement of the beam power and a control of the low injection level in order to avoid any change in the local transport properties. (ii) a measurement of the reflection coefficient at the device level.

Morever, the principle of carrier generation by light is different in comparison to that by electrons: (i) a photon with energy excess than the band-gap of the material generates a single electron hole pair; (ii) since light absorption follows an exponential law, it is not possible to define a maximum penetration depth in the sample; (iii) recently, the finite beam cross section and divergence has also been taken into account. Since the LBIC mode would not add any excess charge to the specimen under test, this can be a major advantage, especially for high resistivity material.

On the other hand, a contrast mechanism is necessary to interpret quantitatively the LBIC signal for a specific defect. For example, Marek has recently developed a theoretical model giving the photocurrent in the vicinity of grain boundaries. The diffusion length and the recombination velocity at the grain boundary are obtained by fitting the theoretical and experimental photocurrent profiles. In the next part of the paper, a description of a high spatial resolution apparatus designed for a precise analysis of the local photovoltaic properties is given. Usually, a GaAs laser diode (780 nm in wavelength) is used in pulsed mode. This wavelength is well suited for Si material (the carriers are generated by the light upon 10 µm) and also for the study of the window effect and the AR coating behaviour in the case of III-V solar cells. The numerical photocurrent value for each geometrical point is averaged in order to get a good signal/noise ratio and the associated value is transferred to the computer memory . The total image is stored under a matrix form (M lines, N columns) corresponding to the investigated area . A grey level or false color two-dimensional topography is obtained on the color display monitor by selecting i photocurrent intervals associated with i levels. Since 1984, the LBIC quantitative mapping technique has been used to obtain several physical parameters such the intra grain diffusion length, the recombination velocity for minority carriers at the grain boundary (polycrystalline silicon device) or the recombination velocity at the front-window interface (III-V device). A comparison between the system presented and other similar commercially available devices such as Scanning Optical Microscope is given.

ELECTRON AND PHOTON-MATTER INTERACTION

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United Kingdom

Many physical phenomena that result from the interaction of a probing beam with a solid target material depend on the beam energy dissipation. Whether the purpose of the experiment is to study defects in a specimen, or to characterize physical properties, energy dissipation is the link between the beam parameters and the measured signals (e.g. charge collection current, cathodoluminescence light emission, X-ray generation secondary and back-scattered electron generation).

Other factors are intrinsically related to research work in the field of defect studies in semiconducting materials. The specimens studied are usually in the form of completed, or almost finished devices. Their geometry can vary between production runs. either because of preparation conditions or from design changes. A great part of the work done is carried out for quality control, or failure analysis. Results of such research are usually required on a short time scale.

The energy dissipation of a probing electron-beam inside a solid target can be determined using empirical relations, mainframe Monte Carlo simulations of a large number of electron trajectories. or simplified Monte Carlo calculations run on micro-computers. The last approach will be presented in detail here. It satisfies the requirements for speed and flexibility with respect to specimen geometries. and can be easily adapted to almost any type of experimental situation. It will be shown that, in many instances, these methods are the only choice available.

The simulation is carried out on micro-computers. taking as input the specimen geometry and composition. and the beam parameters. The calculation is based on the Bethe energy loss relation and an empirically modified Rutherford relation for scattering of electrons. The results consist of a graphical display of electron trajectories, an energy dose plot, and a two dimensional matrix of energy deposition in the specimen. This last output is used for the evaluation of the required signals from the specimen, taking into consideration its electrical and structural (defect) characteristics.
Results from such Monte Carlo simulations and their comparison with experimentally evaluated data will be presented. These will include work with heterojunctions and Schottky diodes with non-negligible metal layers, and charge collection current evaluations from cross-sectional linescans.

For light probe excitation no such methods are available. With the increasing interest in techniques such as LBIC (light beam induced current) and PL studies. and with the increase in resolution of these techniques. it is possible that such methods will be developed.

Performance and Applications of a STEM-Cathodoluminescence System

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Abstract

This review will start with an outline of the key features which need to be incorporated into STEM-CL systems. A detailed evaluation of their performance in comparison with SEM CL systems will be made, and also with the characterisation of defects in semiconductors which is possible by photoluminescence. Advantages and disadvantages will be reviewed and the importance of working with a ion-free electron source will be stressed.

Next will follow a review of the performance of STEM-CL systems in terms of spectral resolution, spatial resolution, time resolution, temperature attainable and pumping levels achievable. Thin foil artefacts which contribute to CL maps will be discussed and evaluated, specimen preparation strategies will be described.Thickness dependence of spectra will be considered.

The application of STEM-CL to studies of point, line and planar defects in semiconductors will be explored. Impurity concentration effects will be discussed, results from threading and interface dislocations reviewed, together with stacking faults, interface steps, twins, precipitates and oval defects. This review will include substrates, epitaxial layers, conventional heterostructures, quantum wells and quantum dots. The materials used as illustrations will include silicon, III-V and II-VI semiconductors as well as ternary alloys.

In conclusion, some attention will be given to the study of electron radiation damage effects and to the combination of EBIC with CL in STEM systems.

POSTER ABSTRACTS

EBIC MEASUREMENTS ON LOW ANGLE GRAIN BOUNDARIES

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The largest grains in Polix ingots contain several low-angle grain boundaries. The electrical properties of high angle grain boundaries have extensively been studied by EBIC/TEM techniques (1) but comparatively less attention has been paid to those of low-angle grain boundaries. However for Polix materials, in the regions of large grains, the total length of low-angle grain boundaries can be much greater than that of high-angle grain boundaries. Moreover, in general the low-angle grain boundaries exhibit strong EBIC contrasts suggesting that their electrical activity is at least of the same order of magnitude than the electrical activity of high-angle grain boundaries.

In this paper, EBIC measurements were performed on several low-angle grain boundaries. The samples are cut in as-grown Polix ingots doped with boron at the doping level 2.10^{16} at.cm^{-1}.

From the EBIC contrast profiles the recombination velocity of the minority carriers at the boundary plane is determined (2).

It is found that the majority of the low-angle grain boundaries are of tilt type, i.e. the rotation axis is located in boundary plane, parallel to the dislocations lines.

For the low rotation angles ($\theta \leqslant 0.5°$) the boundaries lie in {110} planes which are straight on a very long distance. There is only one family of edge dislocations with a Burgers vectors $\vec{b} = \frac{1}{2}$ ⟨110⟩ normal to the boundary plane. In general, these low-angle grains boundaries are free of precipitates.

For the middle range rotation angles ($0.5° \leqslant \theta \leqslant 2°$) the boundaries are facetted. The dominant facet planes are {110} or {111} and in some cases {211}. In the {110} facets there is one family of edge dislocations $\vec{b} = \frac{1}{2}$ ⟨110⟩. The {111} facets contain either one family of identical Frank partial dislocations $\vec{b} = \frac{1}{3}$ ⟨111⟩ or a distribution of three different families $\vec{b} = \frac{1}{2}$ ⟨110⟩. These boundaries often contain small precipitates located on the dislocations.

For the high range rotation angles ($2° \leqslant \theta \leqslant 7°$), in addition to these configurations more complicated ones are observed involving {331}, {431} facets. These boundaries contain a high concentration of precipitates.

The observed boundaries show recombination velocities V_s in the range 1.8 10^4 cm s^{-1} to 15 10^4 cm s^{-1}. For the low and middle range rotation angles, V_s increases linearly with the density of dislocations ; V_s is roughly constant for the high range rotation angles. EBIC measurements have also been performed on low-angle grain boundaries intersecting at a triple junction. It has been noticed that in the range of low rotation angles, the EBIC contrasts and recombination velocities V_s show an additive behaviour at the junction. This fact supports also the idea that V_s is roughly proportionnal to the dislocation density for low rotation angles.

These observations suggest that there are different mechanisms of minority carrier recombination. One of the parameters on which depend the actual mechanism playing a role is the dislocation density.

1 - A. Bary and G. Nouet, J. Appl. Phys., 1988, 63, 2.

POSSIBILITIES OF FORMATION OF BRIGHT EBIC CONTRASTS DUE TO CRYSTAL DEFECTS IN SILICON

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Besides the usual, well understood dark recombination contrasts, also bright EBIC contrasts can be found at extended crystal defects in silicon. Often they appear as bright haloes around dark contrasts, but sole bright contrats are observed, too.

Different mechanisms may lead to the formation of such phenomena, thus rendering clear identification of the contrast origin difficult sometimes.

The poster discusses the possible origin of bright-contrast phenomena, except phenomena caused by microplasmas and surface structure. The following effects are illustrated by examples:

- doping inhomogeneities
  - contrast due to increased width of the junction space-charge region
  - contrast due to plasma screening
- lifetime enhancement within getter zones
- charge collection by defect-own space-charge regions
- repulsion of minority carriers by charged defects
- other, injection-dependent effects.

Up to now there are no models available to describe these contrast phenomena in a quantitative manner.

A New Approach for the Physical Interpretation of Temperature Dependent EBIC Contrast Measurements

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During the last decade several attempts have been made to obtain spectral information about defect levels in silicon with temperature dependent EBIC measurements, but no generally accepted model for the interpretation of the results has emerged. Some of the models even come to contradictory results [1,2].

We will present a new model, which is based on the application of recombination statistics (Shockley-Read-Hall) to the localized defect levels in the bandgap of the semiconductor. The temperature dependence of the thermal velocity of the charge carriers ($\propto \sqrt{T}$) on the one hand, and the influence of the defect level and the Fermi energy position on the other hand lead to a maximum in the recombination rate via this level, if the recombination rate is analyzed as a function of the sample temperature. The EBIC contrast, which is a direct measurement of the recombination activity, reflects this dependence, if the geometrical contributions to the contrast (i.e. mainly the diffusion length L of the minority carriers) are assumed to be constant throughout the measured temperature range.

A re-interpretation of experimental results on dislocations obtained by Ourmazd [1] and Wilshaw and Booker [2] shows the applicability of this model. A common feature of many experiments, as observed by Jakubowicz et. al. [3], finds a simple explanation as well as differences between measurements of Kimerling et. al. and own measurements on individual stacking faults.

We will also present measurements of defects related to substitutional gold in silicon, which exhibits the double peak structure expected for two levels in the bandgap. The temperature, where the peaks appear can be analyzed and yields the two main levels of substitutional gold.

(1) A. Ourmazd: Cryst. Res. Tech. 16, 137 - 146

(2) P.R. Wilshaw, G.R. Booker: Proc. Microsc. Semicond. Mat. Conf. IV, Oxford (ed. A Cullis, D B Holt, Inst. Phys. Conf. Ser. 76, Hilger, Bristol 1985)

(3) A. Jakubowicz, H.-U. Habermeier, A. Eisenbeiss, D. Käss: Phys. stat. sol. (a) 104 (1987)

(4) L.C. Kimerling, H.J. Leamy, J.R. Patel: Appl. Phys. Lett. 30, 217 (1976)

Photocapacity study of *grain boundary recombination in silicon* (*)

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Key features of the grain boundary recombination in semiconductors derive from the limitation of the electron and hole flows to the interface, due to diffusion through the potential barrier of the boundary. There follows a feed-back effect in the process of recombination, as the electrostatic potential in the barrier is determined in turn by the charge state of the boundary traps. To our knowledge, no satisfactory account has been given so far of this feedback effect on the kinetics of grain boundary recombination. To obtain a consistent picture of the electronic processes taking place at the interface, one has thus to write down a set of coupled equations describing (i) the diffusion of the carriers through the potential barrier of the boundary; (ii) the recombination of electrons and holes at the boundary traps (Shockley-Read recombination statistics); and (iii) the relationship between the variation of the electrostatic potential in the barrier and the occupancy of the boundary traps (Poisson equation). These equations allow one to determine the magnitude of the boundary charge and the recombination current as a function of the density of injected carriers. Last, by computing the current density through the interface for a small ac applied voltage, one obtains the expression for the complex impedance of the boundary, that one needs to interpret the transport properties of a bicrystal under light illumination.

In order to check the validity of this approach, we have carried out an experimental study of grain boundary recombination by the means of photocapacity measurements on an n-doped silicon bicrystal. The experimental setup consists of an optical bench fitted with a YAG laser (1.06μ) and a defocusing device to monitor the density of minority carriers injected in the specimen. A light chopper and a lock-in amplifier have been used to detect the photocapacitance signal at low injection levels. The measurements have been made on a bicrystal, whose boundary states had been previously characterised by Deep Level Transient Spectroscopy (DLTS) [1], and known to reduce to a single level of a known density and energy location. The only fitting parameters left in the model are thus the majority (electron) and the minority (hole) carrier capture cross-sections. By adjusting the theoretical master-curve to the experimental data for the variation of the photocapacity vs. the density of injected carriers, we find for the electronic capture cross-section of the boundary traps the value of $(2.0\pm0.5)\times 10^{-12}$ cm^2. The adjustment is found practically insensitive to the value taken for the minority carrier capture cross-section: this can be readily explained in the framework of the model, as the majority carrier density at the interface is actually less than that of the minority carriers due to the barrier effect of the boundary. The majority carrier capture cross-section is therefore the dominant parameter of the recombination at the boundary traps, contrary to what would be expected in the case of recombination centres in the bulk.

This study also provides a new method of determining the recombination velocity of the boundary. The value deduced from the photocapacity measurements is about 15 m/s. It would be interesting to check this value against that obtained by experiments of a different type (Electron or Light Beam Induced Current measurements), on a similar specimen.

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(*) This study is part of D. Bernard's doctoral thesis in physics.

LIGHT BEAM INDUCED CURRENT IMAGING
OF THE ELECTRICAL ACTIVITY OF STACKING FAULTS IN CZ SILICON

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ABSTRACT

Microscopic inhomogeneities in the electrical properties of semiconductors are of great importance to device performances, particularly in advanced device technology. Then in the last few years great attention was paid to the processes which can change the material microstructure, and, above all, to the gettering techniques, on account of their wide impact on the overall yield of electronic tailored materials. With this aim, therefore, extended investigations were carried out, mainly by electron and optical beam testing. In this respect, we report here some results of a spectroscopic analysis performed on Si intrinsically gettered samples by a scanning photocurrent microscopy technique[1] similar, in principle, to the light beam induced current (LBIC) method. However, some differences in the experimental set-up have turned out to be fundamental from the point of view of the instrument-sample interaction and, then, of the information obtainable by the induced photocurrent signals. To probe the material, an above-band-gap energy light from an halogen lamp is focused onto the sample, where a Schottky barrier was provided. The light path is intercepted by interferential filters in the visible-infrared range, so as to select the beam wavelength. To probe point-by-point the object, the sample is moved in a raster fashion across a stationary spot. As in EBIC and LBIC methods, the electron-hole pairs generated by the beam give rise to an induced current $I(x,y)$. This current is measured as analog signal corresponding to the irradiated point, amplified by the lock-in technique, converted from analog-to-digital form and, lastly, noise-cleaned by filtering algorithms. This procedure makes it possible to detect current changes as low as $10^{-14}-10^{-15}$A.
Since a defect causes a local variation in the photoinduced carrier concentration, it is detected by the induced current changes. It should be pointed out that the investigation method described above and from now on called IRBIC (Infra-Red Beam Induced Current) method, even if very similar to the LBIC one, differs from it for an essential element: the extremely low injection level. The use of an halogen lamp as light source, instead of the laser employed in the LBIC method, gives very low values of irradiance. This gives rise to problems in the signal processing, but, on the other side, generates a very low bulk current level (as low as 10^{-13}A), allowing the detection of current changes equal to some parts per cent of this value. In LBIC mode [2] the rate of above-band-gap photon emission from a 1-mW He-Ne (6328A) laser produces $3.2 \cdot 10^{15}$photons$\cdot$sec^{-1}. Usually it is supposed that the beam is attenuated by an amount $\alpha \approx 0.01$, so that, on impinging the semiconductor surface, $3.2 \cdot 10^{13}$ electron-hole pairs are generated per second. In our investigation we examined the samples with a beam power equal to $3.6 \cdot 10^{-8}$mW. The electron-hole pair generation rate G was calculated by the expression [3]: $G = P_b Q(1-\tau)/(qE_g)$ where P_b is the beam power, Q the quantum efficiency, τ the back-scattering coefficient, q the electronic charge and E_g the band gap. In our experimental conditions G is $1.2 \cdot 10^{8}$sec^{-1}. The intensity of the light impinging on the sample resulted a decisive factor in the imaging the electrical activity of the stacking faults. Moreover, due to the ease of changing the wavelength of the light beam probing the sample, depth profiling of the stacking fault electrical activity was obtained. By this way we detected the occurrence of minority carrier recombination and generation processes at some stacking faults, corresponding, respectively, to dark and bright levels in a grey-shade imaging. A possible explanation based on the presence of fixed charges [4] at the defect-silicon matrix interface is proposed.

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EBIC measurement of bulk and surface recombination in p-type silicon : Influence of oxidation and hydrogenation

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Effect of oxygen and hydrogen was studied in both single-crystal and solar-grade polycrystalline p-type silicon.

The variation of EBIC collection efficiency versus voltage was used to characterize both the local minority carrier diffusion length and the surface electrical activity.

Preliminary experiments were made to check the effect of different polishing processes. It was found that industrial basic liquids diminished the diffusion length. Best results were obtained by standard diamond polishing followed or not by copper nitrate mechano-chemical polishing. Final preparation with HF , HNO_3 , CH_3COOH mixing was used in all cases.

Hydrogen was introduced by low energy plasma and oxygen by surface oxidation at 1000°C in dry O_2 . The oxide film was removed with HF before deposit of the Schottky contact (Al thermal evaporation).

The collection efficiency at low beam voltage was enhanced by hydrogenation, indicating passivation of surface states. However the images of the hydrogenated samples showed dark zones indicating that surface was damaged during plasma treatment. No EBIC could be obtained from oxidized samples, an isolant film - non etched by HF - is supposed to have formed. Plasma hydrogenation of these samples restored collection efficiency up to what was obtained in unoxidized hydrogenated samples.

Further experiments are in progress to understand oxygen and hydrogen influence on silicon near-surface electrical activity.

Beam induced variations of GaAs cathodoluminescence : effect of hydrogen and deformation

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We use cathodoluminescence (CL) in a scanning electron microscope to study deep level recombination in semi-insulating GaAs. Two kinds of specimens were examined (i) as-grown crystals before and after hydrogenation, (ii) crystals deformed at high temperatures before and after hydrogenation. Hydrogen is introduced into the crystal using a R.F. hydrogen plasma (T = 240°C, t = 90 min.). A consequence of the introduction of hydrogen is a substantial increase of the light emitted under the electron beam, due to a passivation of deep level centers [1].

For a static beam, the CL intensity decays with time in as-grown crystals whereas it increases towards a maximum in the same hydrogenated crystals; for long time, the light emission finally decreases. In deformed crystals, and before hydrogenation, the CL intensity is time independent whereas after hydrogenation it decreases. The characteristics of the variations depend of the beam parameters (intensity, energy). The phenomena are due to defect redistributions which alter the concentration of recombination centers, the defect mobility being enhanced by the electron bombardment. The similar variations have also been observed with a laser beam [2], [3].

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CATHODOLUMINESCENCE AND POSITRON ANNIHILATION STUDY OF DEFECT DISTRIBUTION IN III-V WAFERS

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Positron annihilation (PA) is a sensitive technique for detection of vacancy-type defects in crystals, that has been widely used in recent years to study defects in semiconductors (1). On the other side, CL and other luminescence techniques have been applied (2) to study the defect distribution in semiconductor wafers. In some cases PA can be useful to interpret results obtained by CL-SEM (3). In this work PA and CL have been used to investigate the distribution and nature of defects in GaP:S, GaAs:Te and undoped SI GaAs wafers. CL intensity, dislocation density and vacancy concentration profiles have been measured. The latter has been obtained by positron lifetime measurements.

The results in GaP indicate that vacancies act as competitors of the green CL. From the evolution of CL intensity and positron lifetime during annealing experiments in electron irradiated GaP samples was concluded that P vacancies and not Ga vacancies are the main centers competing with the near band edge CL. Dislocation density has not been found to be directly related to vacancy concentration.

In the doped GaAs no spatial changes of positron trapping vacancies are detected but a higher vacancy concentration than in undoped SI GaAs is deduced from positron results. Band edge CL and dislocation density profiles in the wafers investigated have the same shape only in SI GaAs. Some of the results in doped crystals can be explained by the presence of impurity-vacancy complexes.

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HOLE-DIFFUSION LENGTH AND TRANSPORT PARAMETERS OF THIN CDS FILMS FROM A SCHOTTKY BARRIER

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The minority carrier diffusion length of semiconductor thin films in polycrystalline form is determined with a good precision by EBIC and LBIC techniques [1,2]. The electron or laser beam used is scanned across the junction. The principle applied in these cases might be attractive for the semiconducting hand side of liquid Schottky barriers. However, these techniques cannot be easily used for such junctions. The methods based on the Gardner approach [3] remain so far more convenient here, especially when very thin films are concerned. In this context, two independent techniques, namely, the surface photovoltage (SPV) [4] and the photoelectrochemical [5] measurements served in this work.

The optoelectronic and transport properties of thin sprayed CdS films, having a thickness of less than 2 µm are reported [6]. The two techniques used led to a good agreement in the hole-diffusion length values. These range from 0.017 to 0.15 µm and behaved differently in two zones. A rapid increase of this parameter is observed below a film thickness of 0,4 µm. Above this thickness, the value obtained is constant Specific space-charge widths are expected because of the respective measurement conditions. The hole-diffusion length decreases as carrier density increases. The hole lifetime shows a regular decreases as the thickness factor increases, while the hole-diffusion coefficient and mobility patterns are similar to that of the photocurrent.

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BY SIMULTANEOUS EBIC/CL MEASUREMENTS

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Both Electron-Beam-Induced Current (EBIC) and Cathodoluminescence (CL) offer the possibility to study defects in III-V compound semiconductors with a lateral resolution of about 1µm.

With a new method, which uses the simultaneous measurement of both signals, it is possible to distinguish between different influences on signal strength (defect structure, defect geometry, decoration etc.) and an excellent reconstruction of the defect geometry can be achieved[2].

Although this method is a very useful tool to characterize defects in direct gap semiconducters, there are some material dependent difficulties to measure the required signals when observing temperature-induced changes in defect recombination properties (degradation of contacts, surface contamination etc.). We have overcome these problems and in this paper we will report on the application of this technique to investigate the role of impurity gettering and decoration on the recombination behaviour of defects in GaAs.

In our experiment we diffused Copper into the crystal. We observed an increase of the EBIC- and the CL-contrast and changes in the contrast profiles. With the help of computer simulations these experimental results can be interpreted as a homogeneous decoration of the defects and the formation of precipitates.

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LBIC ANALYSIS FOR GRAIN-BOUNDARY CHARACTERIZATION IN INHOMOGENEOUS MATERIALS

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The interfacial recombination velocity S of Grain-Boundaries (G.B.'s) may be evaluated by means of LBIC scan line at wavelength $\lambda \geqslant 940$ nm using a finite diameter light spot. ZOOK /1/ has proposed a method to determine S, based on the photocurrent attenuation within a G.B., assuming that the minority carrier diffusion length L in the grains is constant. This assumption is not experimentally verified and causes large errors in the S evaluation.

A model has been developped, using the Green's function method, to compute the LBIC profile at different wavelengths taking in account the local variation of L determined experimentally. This model is valid for different spot diameters and for different thicknesses of samples.

Experimentally, arrays of small diodes (2 mm^2) realized in G.B. containing regions of the material were used to draw the LBIC scan lines and to measure effective diffusion length of minority carrier by the S.P.V. method at different distances from a given G.B. Details of the experimental technics have been given previously /2/.

Figure 1 shows the experimental values (●) of the normalized photocurrent within a G.B., and curve 2 is the profile computed with the present model, while curve 1 is that computed by means of ZOOK's method.

A fairly well agreement is obtained between the experimental points and the model, particularly in the vicinity of G.B.

Directly from the attenuation of photocurrent at G.B.'s the S values can be obtained.

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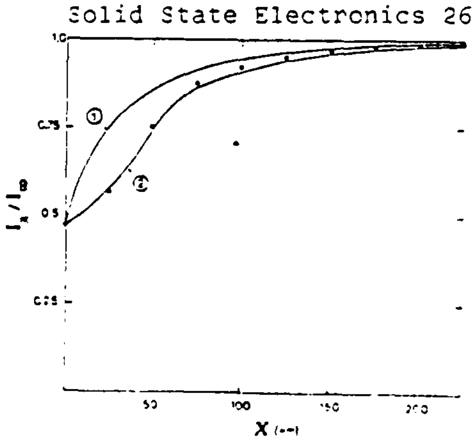

Fig.1. Photoelectric profile near a G.B.
(1) Zock's model (2) Present model
● Experimental results.

RECOMBINATION AT DISLOCATION LEVELS LOCATED IN THE SPACE CHARGE REGION. EBIC CONTRAST EXPERIMENTS AND THEORY.

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Recombination at dislocations located in the space-charge-region (SCR) of a Schottky diode has been previously evidenced by EBIC contrast experiments [1]. A depth-dependent recombination probability was then phenomenologically ascribed to the dislocation, in order to fit theoretical EBIC curves of dislocations perpendicular to the surface with experimental ones. A variable radius $\varepsilon(z)$ was assigned to the recombination cylinder which described the dislocation [2].

We propose a physical model associated with intrinsic dislocation properties to describe the origin of such EBIC contrasts. They arise from the existence of the dislocation electric field; it results from the interaction of trapped carriers and counterbalances the electric field of the Schottky diode in a limited region of the SCR. Thus, recombination of free carriers at the dislocation is allowed.

The present model is built from a z-dependent occupation probability at the dislocation sites. It is pointed out that the electrostatic potential created by the dislocation charge is, at each site, issued from its very first neighbours. This potential can be therefore evaluated in the whole SCR, even when impurity ionization states are depth dependent.

Free carriers and ionized impurities screening mechanism are taken into account by means of a generalized Debye-Hückel wave-vector [3]. The electric potential and fields within the SCR are numerically computed by solving Poisson's equation.

The z-dependent radius $\varepsilon(z)$ is finally taken as corresponding to the distance from the dislocation line at which the dislocation electric field is equal to that of the Schottky diode.

EBIC contrasts are simulated by taking a 100% recombination efficiency within the capture cylinder, and a 100% collection efficiency outside. Calculated EBIC curves versus beam accelerating voltage and reverse bias fit quite well the experimental ones performed on a n-type CdTe specimen ($n=3\times10^{15}$ cm^{-3}). It is particularly found that the dislocation level position needed to get the best fit seems to be near the top of the valence band. These results show that a qualitative spectroscopy of dislocation states can be undertaken by such EBIC contrast experiments and analysis.

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Majority Carrier Assessment by EBIC: Determination of Dopant Concentration at Composition Inhomogeneities

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The EBIC mode of an SEM has generally been used to measure the minority carrier properties of semiconductors such as diffusion length L. However, also majority carrier properties, i. e. dopant concentration, can be quantitatively assessed by EBIC if due account is taken of the space charge region (SCR) associated with the Schottky or p-n junction used for charge collection /1/. If energy-dependent EBIC /2/ is used, the SCR width W is obtained by best fitting of the theoretical EBIC efficiency (dependent on L and W) to the experimental one. Dopant concentration is then inversely proportional to W squared. The greatest accuracy in the determination of W (hence in dopant concentration) is achieved when L is small ($\leq 1\ \mu m$). For high values of L ($> \sim 3\ \mu m$), EBIC efficiency is much less sensitive to W changes because the diffusion current of the electron-beam-generated minority carriers is much greater than the drift current, which is mainly affected by W, so that W determination becomes less reliable. The method is, thus, very well suited for the evaluation of the majority carrier properties in low diffusion length semiconductors, like the bulk III-V compounds (GaAs, InP). Moreover, higher sensitivity is achieved for low doping levels ($\sim 10^{16}\ cm^{-3}$) than for high doping levels ($> \sim 10^{18}\ cm^{-3}$). EBIC measurements of dopant concentration at composition inhomogeneities (growth striations) have been carried out in GaAs crystals. Evaluation of dopant density obtained by EBIC has been checked by comparison with the average dopant density measured by capacitance-voltage characteristics in the EBIC Schottky diode, and by measurement of W as a function of reverse bias. Very good agreement has always been found. The method has also been used to calibrate the photoetching technique in n-type GaAs /3/. It has, thus, been possible to establish the etch rate dependence on dopant concentration which resulted to be exponential over about one decade of dopant density, smaller etching rates corresponding to higher dopant concentration. The latter result is explained as being due to changes in the width of the depletion layer associated with the band-bending at the etching solution-semiconductor interface. In fact, since six (photogenerated) holes are necessary to dissolve one GaAs molecule at the surface /4/, the fewer the available holes the lower is the etching rate. Therefore, low doped regions exhibit higher etching rates than the highly doped regions because the surface depletion layer (where the holes most likely do not recombine) is larger for the low doped regions than for the high doped ones.

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On the Two-Dimensional Determination of p-n Junctions with the EBIC Collection Probability

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Both the intrinsic defect structure in semiconducting materials and the technological steps during microcircuit manufacturing (e.g. implantation, rapid thermal processing) affect the diffusion process of dopants. Using the electron-beam-induced current (EBIC) technique it is possible to determine in an experimental way the site of the space charge region and of the electrical p-n junction, respectively.
In this paper the capabilities of reconstructing the one-dimensional depth distribution $\varphi(z)$ and the cross-sectional distribution $\varphi(x,z)$ of the charge collection probability $\varphi(\underline{r})$ are discussed. Based on the assumption, that $\varphi(\underline{r})$ achieves its maximum value at the site of the electrical junction, $\varphi(\underline{r})$ can be used for the p-n junction delination from EBIC measurements. This practical method of EBIC data interpretation suits in situations, in which the material parameters of the devices under investigation, i. e., the diffusion length of the minority carriers and the surface recombination velocity, are widely unknown.
The starting point in our dicussion consists in the recovery of the depth distribution $\varphi(z)$ from EBIC collection efficiency measurements by both, a trial-and-error method (POSSIN, KIRKPATRICK 1980) and an analytical solution of the inversion problem (DONOLATO 1986). Emphasis is put on the possibility to determine the two-dimensional charge collection probability $\varphi(x,z)$ from EBIC measurements on cleaved samples.

EBIC MEASUREMENTS OF ANNEALED SILICON BICRYSTALS

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Two silicon bicrystals have been analyzed by EBIC to determine the evolution of minority carrier properties such as diffusion length, L_p, and recombination velocity, V_s, after different thermal treatments. The geometric orientations of bicrystals are 26°62 <001> $\Sigma 13$ and 16°26 <001> $\Sigma 25$. The grain boundary planes are (510) and (710) respectively. Small deviations of the order of 0,15° to the exact coincidence orientation are observed. The thermal treatments were carried out in a high purity argon flow at 450°C, 750°C and 950°C for 2, 24, 48, 75 and 92h.

The concentrations of interstitial oxygen and substitutional carbon were determined from infra-red spectra by measuring the absorbance of 1107 cm^{-1} (oxygen) and 604 cm^{-1} (carbon) bands. The doping rate of the as-grown bicrystals was deduced from $C=f(V)$ plots : 5.1 10^{14} P $at.cm^{-3}$ ($\Sigma 13$) and 3.6 10^{14} P $at.cm^{-3}$ ($\Sigma 25$). For the thermal treatments at 450°C and 750°C the concentration of free carriers in the bulk can vary because of the formation of thermal donors (450°C) and new donors (750°C). So their concentrations were deduced from $V = f(B)$ plots by determining the Hall constant R_H. The parameters L_p and V_s were measured using Donolato's model.

For the as-grown condition, a very slight EBIC contrast is observed for both bicrystals, the recombination of $\Sigma 13$ seems to be slightly higher than that of $\Sigma 25$.

The recombination becomes real for the treatments 75h 450°C and 92h 450°C and a slight increase of the free carrier rate is observed for the $\Sigma 13$ orientation whereas this rate is nearly constant for the $\Sigma 25$ orientation. No significant variation of oxygen and carbon concentrations is detected.

The 750°C treatments are characterized by the formation of a EBIC dotted contrast for the $\Sigma 13$ orientation except for the shortest treatment which shows a homogeneous contrast. For the $\Sigma 25$ orientationn, the contrast varies from homogeneous (2h), homogeneous plus dotted contrast (24h, 48h), homogeneous (75h) and finally dotted (92h). This dotted contrast has been attribued to precipitates but no clear evidence of a decrease of the oxygen concentration has been measured. Conversely, the behaviour of free carriers is more complex and the formation of acceptors can be assumed ($\Sigma 13$).

At 950°C, the EBIC contrast is always dotted for the $\Sigma 13$ orientation except for the shortest treatment (2h), in this case a homogeneous contrast is detected with a very weak dotted contrast. For the $\Sigma 25$ orientation the EBIC contrast is always homogeneous, very strong, whatever the temperature. It is worth noticing that a supplementary band (1225 cm^{-1}) attributed to SiO_x precipitated is detected for the 75h treatment. A decrease of the interstitial oxygen is also measured for the 92h treatment but the supplementary band has not been seen.

Two types of precipitates have been observed by TEM : a homogeneous distribution of small precipitates (≃ 5 nm) and larger aggregates (100 nm). The distance between the largest precipitates corresponds approximately to the distance between the darkest spots observed in EBIC mode.

From these observations, it is clear that, at least, two types of EBIC contrast, homogeneous or dotted, are detected. If the dotted contrast can be due to the largest precipitates, the homogeneous contrast could be attributed to the smallest precipitates.

Reconstruction of the Defect Geometry by simultaneous EBIC/CL Measurements; Theory and Experimental Results

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Electron beam induced current (EBIC) as well as Cathodoluminescence (CL) are widely used to investigate defects in semiconductor materials. A quantification of these methods, however, is difficult, since several possible effects may contribute to the observed contrasts (e.g. geometrical changes of the defect or a varying recombination along the defect).

Recently a new model was proposed [1] to overcome these problems for luminescent materials such as GaAs by a simultaneous measurement of EBIC and CL. The different effects due to the diffusion length L of the minority carriers and the absorption coefficient α of the photons on the two signals allow to determine the local depth of a defect from these measurements. In this way the geometry of the defect can be reconstructed.

Together with the EBIC- or CL-contrast this allows to separate the geometrical contributions to the contrast from the contributions due to a varying recombination strength.

We will present the theory for this new method, together with experimental results on known defects in GaAs to show the excellent agreement between real structure and reconstruction.

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INTERNAL MEASUREMENTS FOR FAILURE ANALYSIS AND CHIP VERIFICATION OF VLSI CIRCUITS

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Chip verification and failure analysis during the design evaluation of very large scale integrated (VLSI) devices call for highly accurate internal analysis methods. After having characterized the first silicon by automated functional testing, classification and statistical analysis can be carried out: In this way a rough electrical evaluation of the material under investigation can be made. Further clues to a faulty device behavior can only be obtained by internal measurements. Serious malfunctions of circuit blocks and internally traced signals can easily be detected by scanning electron beam operation, making use of the qualitative voltage contrast; several individual modes of operation are known, such as voltage coding, logic-state mapping and frequency tracing and mapping, for example [1]. While electron beam testing is indispensable for nondestructive and nonloading measurements on submicron interconnection lines [2] mechanical probing can be used for waveform measurements on less critical geometries, too [3]. Hot spot detection (liquid crystal thermography) can be a very helpful and also nondestructive analysis tool for localization of defective areas [4]. Areas of high power dissipation on the chip can easily be located, because they appear as black spots when the IC-surface is viewed through crossed polarizers in the optical microscope. In situations where there does not appear to exist a direct link between the occurance of hot spots and the actual defective area, the laser is a powerful tool, solving this problem by subsequent cutting of metallization lines [5]. Additionally defect identification often calls for destructive methods like wet chemical and plasma etching followed by light or SEM inspection.

In an extreme case of failure analysis the storage function of a memory device was crippled by systematic defects inside the chip's periphery which could be observed, localized and identified. A further step taken was laser manipulation at the chip level, which restored the chip's functionality [6] The comprehensive analysis strategy used here places a greater emphasis on verifying the failure cause through chip manipulation, resulting in a steeper learning curve during the product development.

Internal measurements on submicron interconnection lines for chip verification call for a highly accurate electron-beam tester. The system performance requirements for CMOS circuits in the sub-μm regime are: a 0.1 μm spatial resolution at a low electron acceleration voltage of 1 kV, and a probe current of more than 1 nA, a temporal resolution of approximately 500 ps, and a voltage resolution of about 20 mV. To fulfill these requirements a new electron optical column has been developed in collaboration with Integrated Circuit Testing GmbH [7]. The main feature of a low-aberration compound spectrometer objective lens is the suppression of line-to-line voltage coupling to less than 2 %. Some examples illustrate that the newly developed electron optical column satisfies all the requirements for internal measurements on VLSI circuits.

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In situ observation of dislocation motion in CdTe using EBIC.

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Abstract

Dislocations in compound semiconductors are thought to be decorated with point defect clouds that may dominate the observed electrical activity. We were able to separate the point defect cloud from the dislocation by *in situ* observation of dislocation motion using a deformation apparatus installed in the scanning electron microscope. CdTe crystals were deformed by compression at room temperature. Concerning the EBIC-contrasts associated with moving dislocations we have distinguished two cases:

1) Some dislocations showed almost no EBIC-contrast between their initial and their final position. Dislocation motion was only detectable by the occurence and growth of a new contrast while the contrast at the initial position slowly disappeared. We have concluded that in this case the EBIC-contrasts were mainly due to point defect clouds which were left behind when the dislocations moved and had to be re-established at the final position.

2) Other dislocations in the same specimen moving in the same direction showed EBIC-contrasts of constant intensity during motion, even at a velocity of up to 10 microns per second. No contrasts remained at the initial positions of these dislocations. In this case the origin of the EBIC-contrast seemed to be fixed to the dislocation line also during fast motion.

Different dislocation types or different types of decorating point defects may be responsible for the different EBIC-contrasts during dislocation motion.

Doping Profile Inspection in Silicon by Low Acceleration Voltage SEM-EBIC

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EBIC micrographs of sectional planes are a common tool for the delineation of p/n-junctions. The EBIC contrast has been interpreted based on models originating from van Roosbroeck /1/ in which the specimen is characterized by a recombination velocity at the sectional plane and a bulk recombination parameter (e.g. the minority carrier diffusion length).

In this work, VLSI devices are inspected at low primary electron accelerating voltages. The EBIC contrast is manifestly dependent on the preparation of the sectional plane (cleaving or lapping with subsequent ion milling with argon or oxygen and with or without additional annealing) and in neither case can be explained by van Roosbroeck's model, since the EBIC maximum does not coincide with the space charge area of the p/n-junction.
Thus, a new model is developed, based on the following assumptions :

A sectional plane introduces surface states, and as a result the fermi level is pinned. The electric field perpendicular to the sectional plane can be expressed in Schottky's approximation.

The minority carrier lifetime beneath the sectional plane is drastically reduced by damage introduced by lapping and sputtering or cleaving. Thus, the carrier separation is governed by the electric field, not by diffusion.

Depending on specimen preparation on p-type silicon an inversion channel may transport minority carriers to the n-type region where they can be detected as beam induced current. On n-type silicon a minority carrier channel does not exist and, thus, a beam induced current can not be detected.

As a result of these assumptions, the collection efficiency η can be expressed as a function of Fermi level position at the sectional plane $\Phi_{B,p}$ (measured from the top of the valence band), the surface lifetime τ_S, the surface mobility μ_S, the primary electron extrapolated range R_G, and the (p-type) doping concentration N_A.

For discussion the doping profiles of several specimens were measured with SIMS or calculated with a numerical simulation program (SUPREM III) and the model calculations are compared to EBIC measurements. For drain profile inspection a resolution of 50 nm is achieved.

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High spatial resolution electron beam induced current.

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Thin samples were used to diminish both beam spreading and effective minority carrier diffusion length, in order to eventually obtain better spatial resolution [1,2].

Schottky contacts were deposed by thermal evaporation of Al on p-Si and of Au on n-Si. The experiments were carried out on bicrystals with the grain boundary (GB) running from thick to thin zones. Recombination velocity of the GB considered ($\Sigma = 25$, annealed) was always greater than 10^3 ms^{-1}.

Contrast width at half maximum diminished with thickness : starting from 10 - 15 μm in the bulk it became $\simeq 1$ μm in zones of 1 μm approximate thickness. The EBIC collection efficiency at that level was, with respect to the incident beam intensity, $\simeq 1$ %. The signal vanished in zones thinner than 1 μm.

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EXTRINSIC ORIGIN OF RECOMBINATION CENTRES AT GRAIN BOUNDARIES IN P TYPE SILICON BICRYSTALS.

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The origin of recombination centres at grain boundaries (G.B.'s) $\Sigma 9$ and $\Sigma 13$ in "CZ" grown bicrystals, doped with 10^{15} cm^{-3} boron atoms, has been investigated. L.B.I.C. scan maps at $\lambda = 940$ nm and global capacitive measurements (C-V plots, DLTS) applied to the space charge region of G.B.'s, have been used. The first technic allows the local determination of interfacial recombination velocity S, while the second one leads to average values of energy E_T, density N_T and cross section σ_T of recombination centres of G.B.'s. Doping atoms profiles can also be obtained within G.B.'s.

The results indicate that the two types of G.B.'s, and particularly $\Sigma 9$ have not a noticeable recombination activity in the as grown bicrystals. Annealings at temperatures about 600°C, at least, during several hours are needed to activate $\Sigma 13$ G.B.'s heterogeneously.

The average values of E_T obtained by DLTS are in the range between 0.4 and 0.5 eV. For such values, it was reported that oxygen or SiO_x precipitates could be the source of these deep levels /1/.

In addition, Batistella et al. /2/ have observed that the activation of G.B.'s is heterogeneous and due to localized recombining clusters.

As the investigated "CZ" silicon contains a large amount of oxygen, it could be assumed that oxygen segregation by G.B.'s explains the enhancement of recombination activity during the annealings. $\Sigma 9$ G.B.'s remain poorly recombining, probably because dopant atoms have been segregated during crystal growth, as suggested by the doping profile within a G.B. given by figure 1.

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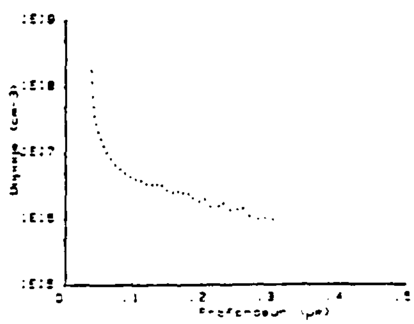

Fig.1. Net density of negative charges in the space charge region of $\Sigma 9$ GB after annealing at 900°C during 24H.

EVOLUTIONS OF GRAIN BOUNDARY RECOMBINATION ACTIVITY IN POLYCRYSTALLINE SILICON INVESTIGATED BY LBIC MAPPING AND DLTS.

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In large grained polycrystalline silicon, the recombination activity of grain boundaries (G.B.'s) is typically heterogeneous. This activity may be evaluated by the determination of interfacial recombination velocity S ; which is related to the presence of deep trap levels at G.B.'s.

Photoconductance and LBIC mapping at $\lambda = 940$ nm have been used to evaluate S, while D.L.T.S. measurements applied to the space charge region of G.B.'s yield activation energy E_T, density N_T and capture cross section σ_T of associated centres.

In as-grown Polyx wafers, S is generally found in the range between 10^3-10^4 cm.s^{-1} and deep trap levels are located within the mid gap.

Annealings in argon at temperatures around 700°C increase S and N_T, while E_T and σ_T remain generally constant. These results indicate that the increase of S is due to that of N_T only, and the nature of the recombination centre source is not changed.

To reduce the recombination activity of G.B.'s, annealings in hydrogen gas flow at 280°C during 2h have been used /1/. The comparison of the measured characteristic values shows that S decreases by one order of magnitude at least. D.L.T.S. indicate that N_T decreases, while E_T and σ_T are not affected by the treatment.

The preceeding results could be explained assuming that hydrogen passivation is not extended to the entire G.B. area and that in the region in which hydrogen has penetrated, all the recombination centres can be passivated. This last evolution is reversible, as annealing the wafers in argon at 350°C during 2 hours is sufficient to restitute the initial value of S, suggesting that Si-H bonds are not formed.

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TEMPERATURE DEPENDENCE OF CL AND EBIC IMAGES OF DISLOCATED GaAs AND Si

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The interactions of dislocations with impurities and/or point defects in GaAs and Si crystals with various thermal histories are investigated by observing the temperature dependence of the CL and EBIC images. Since the impurity distribution around a dislocation changes drastically with temperature, the specimens with different thermal histories show various CL or EBIC contrasts reflecting the distribution of impurities and/or point defects.

(1) CL in GaAs

LEC-grown GaAs crystals doped with different concentrations of Si are studied by means of cathodoluminescence. The observations at room temperature with a S1 photomultiplier reveal the followings. The higher the Si concentration is, the stronger the CL intensity is. The CL contrast is rather uniform throughout the specimen of a high doped crystal, while a contrast pattern related to the distribution pattern of dislocations is observed in a low doped crystal. An investigation[1] is done to see how the CL contrast pattern is influenced by thermal history of the specimen with a low doped crystal with Si the electron concentration of which is 1×10^{16} cm^{-3}. In an as-grown crystal the grown-in dislocations are observed as dark spots with bright regions around them. A specimen rapidly cooled after annealing at 1050℃ shows a uniform CL contrast. On the other hand, the specimen slowly cooled from 1050℃ shows the CL contrast similar to that in the as-grown crystal. This results from the interaction between dislocations and the non-radiative recombination centers. Various heat treatments of the specimens reveal that the impurities related to non-radiative recombination centers are gettered by dislocations most effectively at temperature around 750℃.

Temperature dependence of the CL contrast is studied with the same specimen using a Ge detector. The spatial distribution of CL intensity shows a quite complicated change with respect to the temperature of the observation. The CL intensity is rather uniform at temperatures below 40K irrespective of dislocation distribution. In the temperature range 50 to 80K the CL intensity around a dislocation becomes strong. At 120K another contrast pattern which is not related to the dislocation distribution is developed. At room temperature the regions in the vicinity of dislocations show much stronger CL than in the regions far from dislocations.

(2) EBIC in cast Si

Cast Si crystals (p-type ; B doped) annealed at 800℃ are studied by EBIC technique[2]. The specimen quenched from 800℃ shows dark contrasts along dislocations. On the other hand, the specimen slowly cooled from 800℃ does not show such contrast around dislocations at room temperature. However, it shows the similar contrast as in the quenched specimen below 120K. On the assumption that recombination occurs via one shallow acceptor level and the hole occupation probability of which is proportional to the recombination efficiency, the energy levels of the recombination centers are determined to be $E_V + 0.38$eV and $E_V + 0.11$eV for the quenched and the slowly cooled specimens, respectively, from the analysis of the temperature dependence of the contrast pattern. They correspond to the levels of Fe interstitials and Fe – B pair, respectively.

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MICROSCOPIC AND MACROSCOPIC EVALUATION OF THE RECOMBINATION CONTRAST IN PLASTICALLY DEFORMED AND ANNEALED SILICON BY MEANS OF EBIC-SEM

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Single crystalline silicon bars were plastically deformed in the temperature range 850°C - 1200°C and annealed for periods ranging from 0 - 1 hour.

The recombination contrast in the crystals was assessed on both a microscopic and on a macroscopic level by using different Schottky contact and electron beam scanning geometries.

In particular, a special through-Schottky contact imaging technique was developed that enabled evaluation of the minority carrier diffusion length over large crystal areas (200μm x 200μm) while still resolving recombination contrast from individual defects in the crystal. This technique was facilitated by using a special beam current measuring mechanism in the collection circuitry and, with the aid of some theoretical manipulations, enabled the accurate experimental determination of the collection efficiency of the Schottky contact for minority carriers as a function of beam position and also as a function of the EBIC signal level. By employing the collection efficiency dependency as a function of the minority carrier diffusion length at high kV injection[1,2], the grey levels in the final EBIC image could be accurately calibrated in terms of the the minority carrier diffusion length. Thus contrast due to recombination at individual defects is preserved while the background EBIC grey level between the defect contrast depicts the value of the minority carrier diffusion length in the vicinity of the defect. This technique therefore has great potential for application in defect gettering studies.

The main results of the study and the detail of the imaging techniques will be presented.

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SEM/EBIC STUDY OF ELECTRICAL PROPERTIES IN BULK AND AT GRAIN BOUNDARIES IN Sb-DOPED GERMANIUM

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SEM/EBIC * technique has been used recently to investigate both bulk and grain boundaries (GBs) electrical properties in germanium polycrystals [1]. In this work, the minority carrier diffusion length has been deduced from Schottky contact efficiency measurements using an original model taking into account the recombination of electronic carriers at the metal-germanium interface [2]. The EBIC observation of GBs shows three different behaviours : i) active suboundaries, ii) inactive suboundaries and iii) inactive highly misoriented grain boundaries. These defects have been characterized from a structural point of view using X-Ray topography (Berg Barrett) and ECP (Electron Channeling Pattern).

The EBIC contrast profiles measured on the active suboundaries have been analyzed using Donolato model [3].

The GBs recombinaison velocity of the holes deduced from these measurements is around 5.10^5 cm/s.

The influence of various heat treatments has been also studied. The results show that the bulk minority carrier diffusion length decreases from 16 μm to 3 μm after an annealing at T = 812°C during t = 2 hours. Moreover, some inactive GBs show a high white EBIC contrast after annealing. It has been shown that this behaviour is a consequence of the hole diffusion length decrease in the bulk.

EBIC measurements have been performed at various temperatures (150K-300K) and for different injection levels. The results show the presence of a hole trapping process at some GBs. Such traps behave as recombination centres when the temperature decreases and/or injection level increases.

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Scanning Isothermal Current Transient Spectroscopy (SICTS) for Deep Level Characterization

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We reported Isothermal Capacitance Transient Spectroscopy (ICTS), with which deep level signals can be obtained spectroscopically under isothermal condition. [1] ICTS was applied to the measurement of deep states in amorphous and crystalline semiconductors. [2,3] This method has an advantage : measurements are made at constant temperature. Therefore, this method is considered to be more suitable for the microscopic spatial characterization than scanning DLTS. [4]

In the present case, we measure current transient signals instead of capacitance transient ones and plot $tI(t)$ vs t or $tdI(t)/dt$ vs t (t is time and I is current). A peak appears at a time corresponding to the emission time constant of a deep level, whose height gives the density of the level. The measurement and signal processing are performed with a computer-aided measurement system. Optical beam pulses from a semiconductor laser are used to fill the deep levels with carriers and the specimen stage is moved mechanically for scanning with the optical beam.

We have applied this ICTS method to the characterization of gap states in undoped a-Si:H films. It has been found that the behavior of transient current $I(t)$ agrees well with that of capacitance and $I(t)$ is due to the thermally excited carriers (holes). SICTS measurement has been performed on the material and the gap state distribution has been obtained.

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DETERMINATION OF ELECTRON BEAM CHARGING CONDITIONS OF OXIDES AT LOW ENERGY IN THE LOW DOSE RANGE

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Scanning Electron Microscope (SEM) voltage contrast techniques proved to constitute a valuable tool for testing integrated circuits (IC). However, the active components may be damaged by electron beam irradiation, so that it is of great importance to determine accurately the allowable limits.

Differents types of effects arise and starting from high to low primary energies, two zones may be distinguished. In the case of classical MOS transistors, if the primary electron (PE) penetrate down the gate oxide, strong charging effects result (1) but if the PE are located on the top oxide above the polysilicon gate only existing flaws inside the gate oxide are influenced by reemitted photons. So the sensitivity of the observed threshold voltages shifts are strongly dependent on the incident beam energy (1,2). In the case of the floating gate MOS transistors, due to the fact the deposited charges by the electrons on the top oxide are not electrostaticaly screened, an additional channel conductance modulation occurs.

The purpose of this paper is to show the achievement of e-beam charging evaluations on insulators using MOS floating gate transistors. This method is achievable in classical SEM without any additional surface preparation.

We present the different ways to obtain quantitative results using either a couple of classical and floating gate transistors either a controlled gate element. The equations governing the electrical characteristics of the floating gate MOS transistors are derived, they show good agreement with the experimental results. The deposited charges may be evaluated both in linear or saturation regions of the devices assuming a previous characterization of the technology used. The negative charging evaluation are obtained in the 2-6 keV range and our method allows the determination the following magnitudes $1.10^{-9}-1.10^{-6}$ $C.cm^{-2}$. Basing on these results, it is shown that surface charge exchanges are necessary to fit experiments and theory in the range considered.

Finally, we have shown the possibility of e-beam charging evaluations on microelectronics insulators, using simple MOS devices, with good accuracy and sensitivity.

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Thickness Dependence of Cathodoluminescence in Thin Films

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Abstract. - Thin film samples have been increasingly used in high resolution imaging studies of cathodoluminescence (CL) from materials, in order to achieve the smallest CL source possible[1-3]. The analysis of the luminescence signals from thin film material is often hampered by the changes associated with the film thickness variation. This thickness effect has been analysed in a simple model which takes into account the diffusion of the excited states in thin films. The electron beam is assumed to provide a uniform excitation density over the entire film thickness appropriate to electron transparent films (the definition of which is also given). The intensity variation of CL signal as a function the foil thickness t is given by the formula $I(t) = I_0\left(t - \frac{2L}{\coth\frac{t}{2L} + f}\right)$

where L is the diffusion length of the energy carrier in a bulk sample; f is the ratio of the bulk diffusion 'velocity' L/τ to that of the surface diffusion velocity s. Both physical parameters can be obtained from a plot of the CL intensity verses the film thickness. This has been applied to a number of materials such as Y_2O_3:Eu^{3+}, YAG:Ce^{3+}, Diamond and InP. For the last two types of materials, the result of the analysis is consistent with those from other experiments[3,4]. For phosphors with a relatively large doping of luminescent ions, the saturation effect caused by an intense excitation density must be taken into account in interpreting the physical parameters deduced[5,6].

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